

Very High Energy Observations of Shell-Type Supernova Remnants with SHALON Mirror Cherenkov Telescopes

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Abstract. The investigation of VHE gamma-ray sources by any methods, including mirror Cherenkov telescopes, touches on the problem of the cosmic ray origin and, accordingly, the role of the Galaxy in their generation. The SHALON observations have yielded the results on Galactic shell-type supernova remnants (SNR) on different evolution stages. Among them are: SNRs Tycho's SNR, Cas A, IC 443, γ Cygni SNR and classical nova GK Per (Nova 1901). For each of SNRs the observation results are presented with spectral energy distribution by SHALON in comparison with other experiment data and images by SHALON. The collected experimental data have confirmed the prediction of the theory about the hadronic generation mechanism of very high energy 800 GeV - 100 TeV γ -rays in Tycho's SNR, Cas A and IC443.

Introduction

The detection of TeV gamma-rays from the number of galactic sources was the major achievement of gamma-astronomy and is providing new insights into the cosmic ray emission mechanisms and their sources. The hypothesis that Supernova Remnants (SNRs) are unique candidates for cosmic-ray sources has been prevalent from the very beginning of cosmic-ray physics. The electron component of Cosmic Rays is well visible on the SNR emission through the wide range of electromagnetic spectrum from radio to low energy gamma-ray emission, but the information on the nuclear Cosmic Ray component in SNRs can only be obtained from high and very high energy gamma-ray observations. So, gamma-astronomic observations can help to solve the cosmic ray origin. We present the observation results by SHALON telescope of shell type Galactic supernova remnants: Tycho's SNRs, Cas A, γ Cygni SNR and IC 443 as well as the classical nova GK Per that is on the earliest SNR evolution stage.

GK Per (Nova 1901)

Nova Persei 1901 (GK Per) is one of the most extensively observed and studied classical nova shells over the entire electromagnetic spectrum. The optical data [1] are demonstrated interaction between the nova ejecta and the ambient gas. Furthermore, remnant of nova is detected at radio energies with the Very Large Array (VLA) as a source of nonthermal, polarized radio emission [2]. The results of these observations show the existence of shocked interstellar material. The X-ray shell around GK Per was first discovered with the ROSAT experiment and then it has been observed by Chandra telescope [3]. In particular, with Chandra observations,

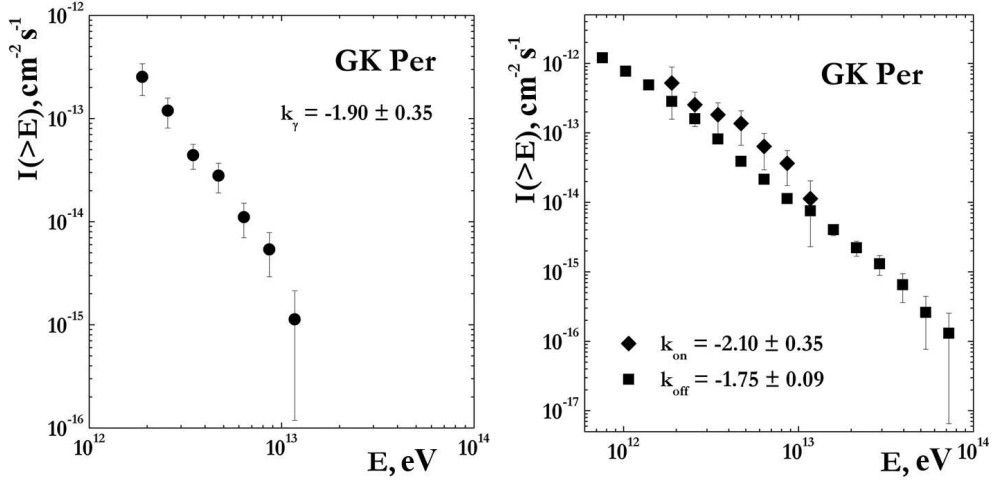


Figure 1. GK Per (Nova 1901) characteristics: **left** - Integral gamma-ray spectrum with a power-law index $k_\gamma = -1.90 \pm 0.35$; **right** - The event spectrum from the source with background with index of $k_{ON} = -2.10 \pm 0.35$ and spectrum of background events observed simultaneously with the object with index $k_{OFF} = -1.75 \pm 0.09$

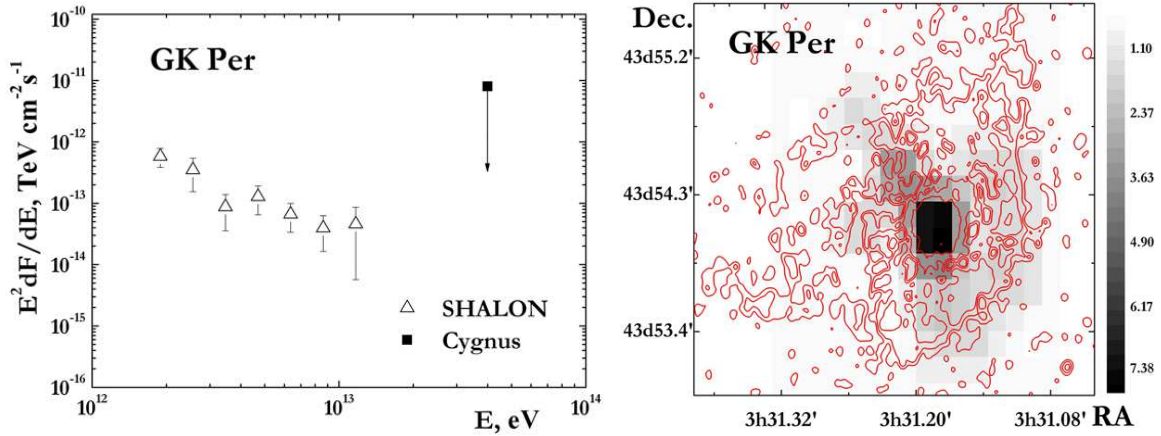


Figure 2. GK Per (Nova 1901) characteristics: **left** - Spectral energy distribution from GK Per (Nova 1901) obtained by SHALON; **right** - The image of GK Per in the energy range 800 GeV - 40 TeV by SHALON the contours indicate Chandra X-ray image of GK Per [3].

the X-ray emission of the same electron population has been detected as the extension from the radio wavelengths. The detection of the X-rays from the supernova remnant shell which are primarily due to bremsstrahlung of shock accelerated relativistic electrons, supposed the detection of gamma-ray emission originated from π^0 - decay, secondary pp-interactions [4] as well as possible contribution emission produced via Inverse Compton scattering [4]. Chandra X-ray data shows that, the nova remnant of GK Per could be a younger remnant that will resemble older SNRs like IC 443 ($(3 \div 30) \times 10^3$ year) which interact with molecular clouds.

In accordance with program on long-term studies of metagalactic gamma-ray sources, fifteen-year-long observations of the central galaxy in the Perseus cluster, NGC 1275, are being carried out in the SHALON experiment [5, 6, 7, 8, 9, 10]. During the observations of NGC 1275 the SHALON field of view contains the source of nonthermal radio and X-ray emission GK Per

(Nova 1901) of classical nova type as it located at 3° North from NGC 1275. So due to the large telescopic field of view $> 8^\circ$ the observations of NGC 1275 is naturally followed by the tracing of GK Per. GK Per as a source accompanying to NGC 1275 was observed with SHALON telescope at the period from 1996y to 2012y for a total of 111 hours during the clear moonless nights at zenith angles from 5° to 35° . The observations were performed using the standard (for SHALON) technique of obtaining information about the cosmic-ray background and gamma-ray-initiated showers in the same observing session. The SHALON method of selecting γ -ray showers from background cosmic-ray showers allow to reject 99.92% of the background showers [5, 6, 7]. The γ -ray source associated with the GK Per was detected above 2 TeV by SHALON with a statistical significance 9.2σ determined by Li&Ma method [11]. The signal significance for this SNR is less than one for the source with similar flux and spectrum index obtained in the same observation hours because of less collection field of view relative to the standard procedure of SHALON experiment [5, 6, 7]. The corrections for the effective field of view were made to calculate source flux and energy spectrum. The average integral flux at energies above 2 TeV for GK Per is $I_{GKPer} = (2.9 \pm 1.3) \times 10^{-13} \text{cm}^{-2} \text{s}^{-1}$ (Fig. 1, left). Figure 1b presents the spectra of the ON- and OFF-events needed to extract the gamma-ray spectrum from GK Per. The gamma-ray spectrum of GK Per (Fig. 1, left) is obtained by subtracting the spectrum of the background events recorded simultaneously with the sources observations, $I_{OFF} \propto E^{k_{OFF}}$, from the spectrum of the events arrived from the source position, $I_{ON} \propto E^{k_{ON}}$ (Fig. 1, right). Taking into account the proximity to a nearby source NGC 1275, we made the observation data procession first associated with NGC 1275 and then with GK Per. We found that 1% of showers are common for the both sources. After the detailed analysis of arrival direction of these showers and angular distance [5], less than 0.5% of NGC 1275 showers were recognized to be GK Per showers. This didn't change the average flux of NGC 1275 form [5, 9, 10]. The energy spectrum of γ -rays in the observed energy region from 2 to 15 TeV is well described by the power law $F(E > 2 \text{ TeV}) \propto E_\gamma^k$, with $k_\gamma = -1.90 \pm 0.35$ (see Fig. 1, left). The spectral energy distribution and the image of GK Per at TeV-energies by SHALON are shown in Figure 2. The analysis of γ -ray shower arrival direction revealed the main TeV-emission region coinciding with the position of central source of GK Per and the weak emission of shell, that is also observed in X-ray by Chandra [3] (Fig.2, right).

Cas A supernova remnant (1680 year)

Cas A is a youngest of historical supernova remnant in our Galaxy. Its overall brightness across the electromagnetic spectrum makes it a unique object for studying high- and very high- energy phenomena in SNRs. Cas A was observed with SHALON telescope during the 68 hours in period of 2010 - 2013 yy [7]. The gamma-ray source associated with the SNR Cas A was detected above 800 GeV with a statistical significance [11] of 16.1σ with a gamma-quantum flux above 0.8 TeV of $(0.64 \pm 0.10) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1}$. The energy spectrum of gamma-rays in the observed energy region from 0.8 TeV to 30 TeV is well described by the power law with exponential cutoff, $I(> E_\gamma) = (0.64 \pm 0.10) \times 10^{-12} \times E_\gamma^{-0.91 \pm 0.11} \times \exp(-E_\gamma/10,3 \text{ TeV})$ (Fig. 3, left). Figure 3 right presents Chandra X-ray image of Cas A (lines) [12] in comparison TeV structure in energy range of 0.8 - 30 TeV by SHALON.

Two favored scenarios in which the gamma-rays of 500 MeV - 10 TeV energies are emitted in the shell of the SNR like Cas A are considered. The gamma-ray emission could be produced via Inverse Compton scattering and by accelerated cosmic ray hadrons through interaction with the interstellar gas and then π^0 - decay. Figure 3, left presents spectral energy distribution of the gamma-ray emission from Cas A by SHALON (\blacktriangle) in comparison with theoretical predictions [13, 14] and other experimental data: Fermi LAT [13], HEGRA [15], MAGIC [16], VERITAS [17]; upper limits of EGRET [18], CAT [19], Whipple [20]. Solid lines show the very high energy gamma-ray spectra of hadronic origin [13, 14]. The calculation results of leptonic model in

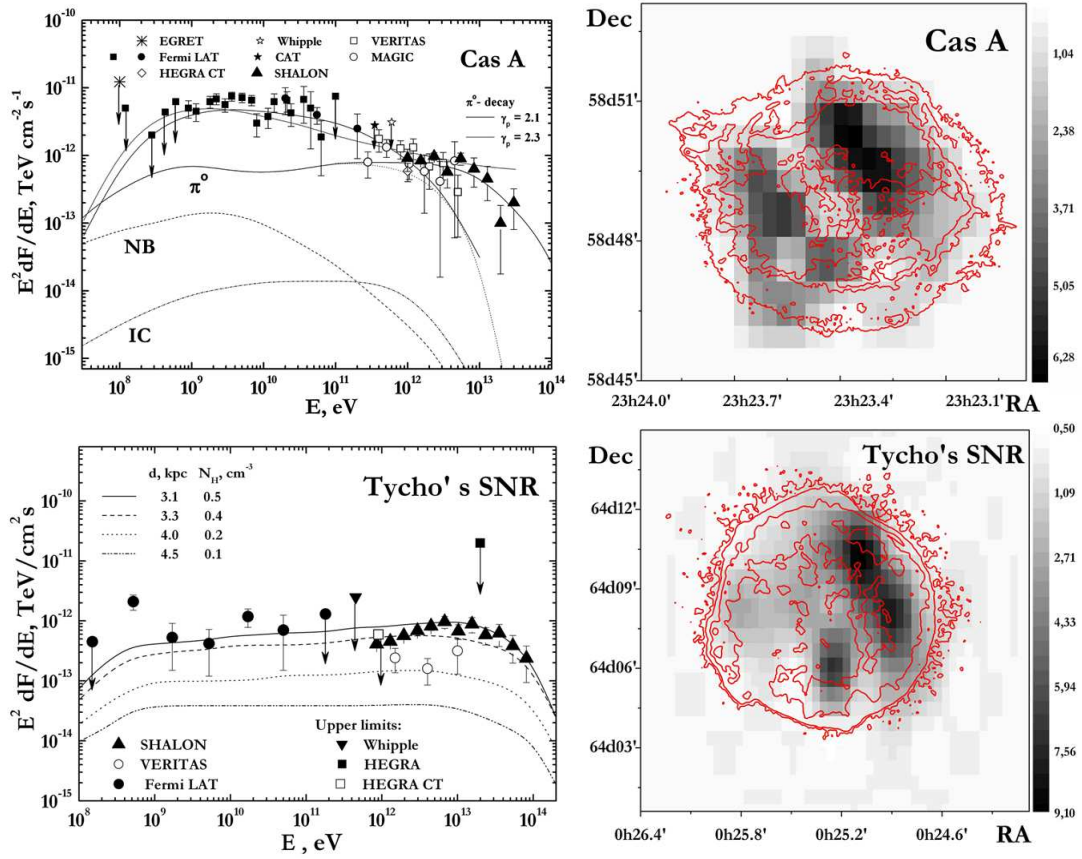


Figure 3. Characteristics of shell-type supernova remnants Cas A and Tycho's SNR. **left** - Spectral energy distributions of high- and very high energy γ -ray emission by SHALON (\blacktriangle) in comparison with other experiments (see text). NB - nonthermal Bremsstrahlung γ -ray energy flux; IC - Inverse Compton γ -ray energy flux [14]; d - source distance; N_H - interstellar medium density. **right** - images of SNRs at energies > 0.8 TeV by SHALON (grey scale); red contours are the X-ray emission by Chandra.

assumption of two magnetic field values are also considered in [13]. It was shown that leptonic model with $B = 0.3$ mG predicts a 5 - 8 times lower gamma-ray flux than the observed; the model with $B = 0.12$ mG, which can broadly explain the observed GeV flux predicts the TeV spectrum with cut-off energy about 10 TeV.

The detection of gamma-ray emission at 5 - 30 TeV and the hard spectrum below 1 TeV would favor the π^0 -decay origin of the gamma-rays in Cas A SNR.

Tycho's Supernova Remnant (1572 year)

Tycho's SNR originated from the Ia type supernova which exploded in 1572 year. The high quality X-ray image of Tycho's SNR by Chandra shows an expanding bubble of debris inside a more rapidly moving shell of extremely high energy electrons. The supersonic expansion of the stellar debris has created two X-ray emitting shock waves - one moving outward into the interstellar gas, and another moving back into the debris. Such the character of displacement of the shock and the contact discontinuity surfaces makes the cosmic ray acceleration at the supernova shock very efficient.

The observations of Tycho supernova remnant are carried out by SHALON telescope in the period of 1996 - 2010 years [6, 7, 8, 9, 10]. Tycho's SNR has been detected by SHALON at energies above 0.8 TeV with a statistical significance 17σ determined by Li&Ma method [11]. The integral gamma-ray flux above 0.8 TeV was estimated as $(5.2 \pm 0.4) \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$. The energy spectrum of γ -rays in the observed energy region from 0.8 to 80 TeV by SHALON is well described by the power law with exponential cutoff $I(> E_\gamma) = (0.41 \pm 0.05) \times 10^{-12} \times E_\gamma^{-0.93 \pm 0.09} \times$

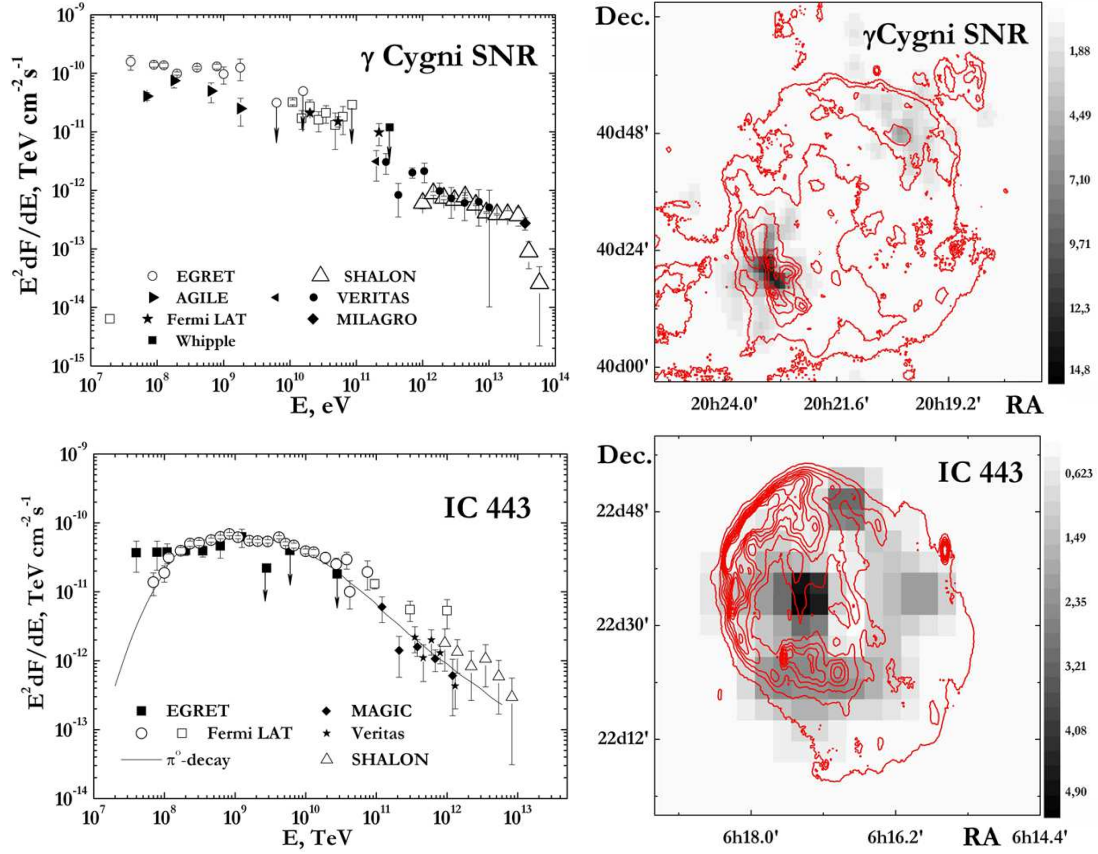


Figure 4. Characteristics of shell-type supernova remnants γ Cygni SNR and IC 443. **left** - Spectral energy distributions of high- and very high energy γ -ray emission by SHALON (Δ) in comparison with other experiments (see text). **right** - images of SNRs at energies > 0.8 TeV by SHALON (grey scale); red contours are radio structure by Canadian Galactic Plane Survey.

$\exp(-E_\gamma/35\text{TeV})$. The image of Tycho's SNR at energies 0.8 - 80 TeV by SHALON telescope is also shown in Fig. 3. Recently, Tycho's SNR was also confirmed with VERITAS in observations of 2008 - 2010 and 2011 years [21]. The γ -ray emission from Tycho's SNR was detected with Fermi LAT in the range 100 MeV - 300 GeV [22]. According to model [23] the expected flux of γ -quanta from π^0 -decay, $F \propto E^{-1}$, extends up to > 30 TeV, while the flux of γ -rays originated from the Inverse Compton scattering has a sharp cutoff above the few TeV. So the detection of γ -rays with energies 10 - 80 TeV from Tycho's SNR by SHALON is an evidence of their hadronic origin.

Due to the high-quality observations from XMM-Newton and Chandra the fundamental properties of the X-ray emission in Tycho, as a SN explosion energy $E_{SN} = 1.2 \times 10^{51}$ erg, which are necessary to model calculations are available. The distance determinations for Tycho's SNR have varied from 2.0 - 2.8 kpc to 3.1 - 4.5 kpc [24]. In order to find a constraint on the source parameters as distance d and the interstellar medium density N_H , we compare the model resulting γ -ray spectral energy distribution [24] with one from γ -ray observations at TeV energies. The additional information about parameters of Tycho's SNR can be obtained in frame of nonlinear kinetic model [23, 24] if the TeV -quantum spectrum of SHALON telescope is taken into account: a source distance 3.1 - 3.3 kpc and an ambient density $N_H = 0.4 - 0.5\text{cm}^{-3}$ and the expected π^0 -decay γ -ray energy spectrum extends up to about 100 TeV (Fig. 3, left). The same parameters have obtained in [25] calculations of structures visible by Chandra at X-ray energies (see red contours in Fig. 3, right).

γ Cygni SNR (age $\sim (5 \div 7) \times 10^3$ years)

γ Cygni SNR is a shell-type supernova remnant at a distance of 1.5 kpc and with the observed diameter of 1° . The shell-like features are known in radio- and X-ray energy regions [26].

γ Cygni SNR is older than Cas A and Tycho's SNR, its age is estimated as 5000 - 7000 years. [26, 28] and it is supposed to be in an early phase of adiabatic expansion. The observations of different age supernova remnants can help to reveal the mechanisms of very high energy cosmic ray acceleration in the SNRs up to energies 10^{15} eV.

γ Cygni SNR as a source accompanying Cyg X-3 is systematically studied with SHALON telescope since 1995 up to now. The γ -ray source associated with the γ Cygni SNR was detected by SHALON [9, 10] above 800 GeV with a statistical significance [11] of 14σ . The average integral gamma-flux above 0.8 TeV: $I_{\gamma Cygni SNR} = (1.27 \pm 0.11) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$. The signal significance for this SNR is less than one for the source with similar flux and spectrum index obtained in the same observation hours because of less collection field of view relative to the standard procedure of SHALON experiment [5, 6, 7]. The corrections for the effective field of view were made to calculate source flux and energy spectrum. The energy spectrum of γ -rays in the observed energy region from 800 GeV to 50 TeV is well described by the power law with exponential cutoff, $(1.12 \pm 0.11) \times 10^{-12} \times E_{\gamma}^{-0.93 \pm 0.09} \times \exp(-E_{\gamma}/20 \text{ TeV})$ [9, 10] (Fig. 4, left). The image of γ Cygni SNR at energies 0.8 - 50 TeV by SHALON is presented in Fig. 4, right in comparison with radio structure by Canadian Galactic Plane Survey (CGPS) (see lines). The analysis of TeV gamma-ray arrival directions reveal two emission regions in γ Cygni SNR: the main at the South-East part of SNR shell and second one at North. The main contribution of energy flux gives the SE region of SNR shell. Also, TeV γ -ray emission regions correlate with the NW and SE parts of the shell visible in the radio energies by CGPS. The VERJ2019+407 source was detected at 200 GeV by VERITAS [29] correlated with the position of northern part of γ Cygni SNR shell. In Figure 3 the spectral energy distribution of the γ -ray emission from γ Cygni SNR by SHALON is presented in comparison with experiment data from EGRET [18], AGILE [30], Fermi LAT [31, 32, 33], VERITAS [29, 34] MILAGRO [35].

IC 443 supernova remnant (age $\sim (3 \div 30) \times 10^3$ years)

The IC 443 is well known for its radio, optical, X-ray, and MeV-TeV energy γ -ray emissions. IC 443 is a shell-type SNR and it has an angular extent of $45'$ in the radio energies with a complex shape consisting of two half-shells with different radii. The age of IC 443 remains uncertain, with various estimates placing it in the range $(3 \div 4) \times 10^3$ yr., but other analysis indicate that it is older $(20 \div 30) \times 10^3$ yr. IC 443 is one of the best candidates for the investigation of the connection among SNRs, molecular clouds and high- and very high energy γ -ray sources. The close placement of the dense shocked molecular clouds and GeV-TeV γ -ray emission regions [36] detected by EGRET, Fermi LAT, MAGIC and VERITAS suggests that IC 443 can be considered as a candidate to the hadronic cosmic-ray source.

IC 443 was detected by SHALON with the integral flux above 0.8 TeV $(1.69 \pm 0.58) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ [10] with a statistical significance of 9.7σ [11]. The integral energy spectrum of IC 443 can be approximated by the power law with index $k_{\gamma} = -1.94 \pm 0.16$. The favored scenario in which the γ -rays of 100 MeV - 7 TeV energies are emitted in the shell of the IC443 SNR is π^0 -decay which produced in the interactions of the cosmic rays with the interstellar gas. Inverse Compton scattering can not explain the observed IC 443 γ -ray emission as there is no bright source of seed photons in the region of the IC 443. The spectral energy distribution of the γ -ray emission from IC443 by SHALON (\triangle) in comparison with other experiment data EGRET, Fermi LAT, MAGIC, VERITAS [36] and with theoretical predictions is shown in Figure Fig. 4, right. Solid line shows the very high energy γ -ray spectra of hadronic origin. The image of IC443 at TeV energies by SHALON is presented in Figure 3 in comparison with radio structure by CGPS (see lines). The analysis of arrival directions of γ -rays with energies 800 GeV - 7 TeV reveal the correlation of TeV γ -ray emission maxima with MeV-GeV emission observed by Fermi LAT [36], also TeV gamma-ray emission of South and South-West parts of IC 443 shell correlated with the position of swept out dense molecular cloud (Fig. 4, right).

Conclusion

The observation results of Galactic shell-types supernova remnants on different evolution stages GK Per (Nova 1901), Cas A, Tycho's SNR, γ Cygni SNR and IC 443 by SHALON mirror Cherenkov telescope are presented. The TeV gamma-ray emission of classical nova GK Per, that could be a shell-type supernova remnant on early evolution stage, was detected for the first time by SHALON. Also, very high energy gamma-rays from the shell of GK Per, visible in the X-rays, were detected with SHALON experiment for the first time. The experimental data have confirmed the prediction of the theory about the hadronic generation mechanism of very high energy γ -rays in Tycho's SNR, Cas A and IC443.

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